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NASA UNCONVENTIONAL ROCKET NOZZLES UTILIZING EXTERNAL EXPANSION

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ABSTRACT

Annular internal-external-expansion rocket nozzles for large-thrust booster applications have been experimentally evaluated in cold-flow studies in the Lewis Research Center 10- by 10-Foot Wind Tunnel in quiescent air and at Mach 2 to 3. These nozzles have external air flowing through the center as well as around the outside of the exiting jet. In essence, these are refined cluster configurations with excellent aerodynamic characteristics in terms of "off-design" performance, base heating effects, and thrust vectoring capabilities. With an area-ratio-25 annular nozzle, the ratio of net to ideal thrust was essentially independent of pressure ratio at below design conditions, remaining essentially constant at approximately 0.98 over a pressure ratio range of 40 to 1,000. Compared to conventional 8:1 convergent-divergent nozzles, this performance could be translated into a 17-percent increase in orbital payload for the same initial vehicle gross weight.

An asymmetric external-expansion "penshape" nozzle has also been demonstrated to have excellent "off-design" thrust performance. This unconventional nozzle design lends itself to unusual packaging arrangements -- a jet canard configuration is used herein for illustration. This canard, in concept, combines aerodynamic and reaction control in the uppermost stage to remove the steering function from the main propulsion system and to take advantage of the large moment arm.

INTRODUCTION

The term "unconventional" is currently in vogue as a catch-all reference to a variety of new rocket nozzle concepts (e.g. references 1, 2 and 3). Most of these designs are aimed at making use of a free-expansion boundary on the jet to obtain good thrust characteristics at less-than-design pressure ratio. In this way, the over-expansion thrust losses of convergent-divergent nozzles can be avoided. From an overall vehicle viewpoint, the use of external expansion in the exhaust nozzle offers many potential advantages in terms of "off-design" thrust performance, external-stream and base-flow aerodynamics, and structural considerations. At the Lewis Research Center, two areas of application for such nozzles have been considered; one, in the main propulsion system of large-thrust boosters where an annular nozzle configuration has been proposed; and two, in a jet-canard configuration on the uppermost stage where an asymmetric external-expansion "penshape" nozzle is provided to generate the required attitude control moments. Subsequent discussion will detail the specific research in these areas.

ANNULAR NOZZLES FOR LARGE-THRUST BOOSTERS

Let us first concern ourselves with some of the booster problems:

Design Philosophy:

To achieve a given large thrust level, three different design approaches involving equivalent convergent-divergent nozzle systems (figure 1) might be considered. First, a single large nozzle might be used. As sketched in figure 1(a), this configuration would be long and could have base heating and gimbaling problems. As an alternate approach, a number of smaller developed and proven engines might be employed. A cluster of smaller but geometrically similar nozzles (figure 1b) would, of course, be much shorter and would probably allow more refined thrust vector control by gimbaling only the outer motors. However, difficult jet interactions and base heating effects would arise and necessitate the use of protective heat shields with their attendant weight penalties. Base heating phenomena (entrainment, recirculation, and ignition of fuel-rich exhaust gases) in both single and multi-engine configurations have been the subject of extensive investigations at the Lewis laboratory for the past several years.

As a third approach, these individual motors might be arranged in a circular pattern in the base and, further, integrated into a single annular motor as illustrated in figure 1(c). This annular design would eliminate the base heating problems by allowing external free-stream air to flow through the center of the nozzle. In essence, this configuration might be considered a refined cluster arrangement with either a single combustor or a multitude of segmented (or cellular) burners (as advocated for the plug nozzle in reference 2) feeding a single nozzle. A simple cursory examination of the nozzle cooling requirements was made wherein it was assumed that the heat-flux distributions through the nozzles were functions only of the one-dimensional area variations. Thus, the heat load or cooling requirements would be reflected in the relative amounts of local wetted surface areas. Solely on the basis of geometric scaling considerations wherein the throat area was conservatively defined as the product of the wetted perimeter times the hydraulic diameter, it was concluded that the total heat load would be no greater for the annular than for a conventional single C-D nozzle. This annular arrangement with external expansion might appear even more favorable from a cooling standpoint in that the free jet boundary in effect eliminates one of the expansion surfaces.

Nozzle Aerodynamics:

From aerodynamic considerations, a combination of both internal and external expansion (figure 2) was selected, the external expansion to improve "off-design" performance characteristics and the internal expansion to minimize boattail angle and the inclination of the sonic line. Prandtl-Meyer flow relations were used to describe both the internal- and external-expansion processes. Flow patterns are illustrated for nozzle pressure ratios below, at, and above the design value. By virtue of the free expansion boundary which adjusts according to the pressure ratio, the flow remains attached to the external ramp at all conditions.

Sufficient internal expansion was incorporated in the nozzle so that essentially complete expansion would be achieved internally at the launch conditions. The flow is then turned back to the axial direction by the external contoured surface through a series of weak compression-expansion waves with the local surface pressures remaining near ambient. With increasing altitude (or increasing pressure ratio) the nozzle flows more and more full until at the design value the flow fills the nozzle and exits uniformly in an axial direction. With further increases in altitude, the flow continues to expand externally without affecting the ramp pressures. The exiting jet would then be mainly flaring out from or into the nozzle centerline, depending on the orientation of the expansion surfaces.

Experimental Apparatus:

To explore the aerodynamic performance of annular internal-external-expansion nozzle configurations, an experimental cold-flow investigation (reference 1) was conducted in the Lewis 10- by 10-Foot Supersonic Wind Tunnel in quiescent air and at Mach 2 and 3. The test apparatus is shown in figure 3. Two nozzles were studied; one with an area ratio of 15 with the simulated jet flow external to the nozzle expansion surface and another with an area ratio of 25 with the simulated jet flow internal to the nozzle expansion surface. The nozzle was supported by four hollow struts from the 9-inch, cylindrical fuselage to provide an annular entry to duct the free-stream air to the center of the nozzle. Rather arbitrarily, the radii of the annular nozzles were selected so that in the one case, $\epsilon = 15$, the nozzle was essentially flush with the fuselage and in the other, $\epsilon = 25$, the annular nozzle was considerably larger ($\sim$15-inch diameter).

Thrust vector control in these annular configurations might well be achieved by flaps on the external expansion surface being deflected into or out of the exhaust jet in an area of the nozzle where the local heat flux is low and some cooling would be in effect from the ambient air on the opposite side of the flap. To explore this technique of vectoring, two such flaps were installed on both annular nozzles. These were located diametrically opposite each other in the pitch plane.

Cold air pressurized up to 600 psia in the nozzle was used to simulate the exhaust flow. Two independent strain-gage balance systems were used, one to determine nozzle thrust and side forces with the jet "on" and the other to determine configuration drags with the jet "off." A flexible bellows prevented leakage of the high-pressure air as it passed across the balance. To define the jet flow characteristics, a survey rake was located in the nozzle exit plane.

Nozzle Thrust Performance:

The annular nozzle thrust characteristics are presented in figure 4 where the ratio of actual to ideal net thrust is shown as a function of nozzle pressure ratio. Ideal thrust assumes a perfect nozzle (complete isentropic expansion to ambient pressure with uniform parallel exit flow at each pressure ratio). For comparison purposes, the performance levels of various convergent-divergent nozzles (reference 4) are also included. The thrust ratio of both annular nozzles ($\epsilon = 15$ and 25) was essentially independent of pressure ratio at below-design conditions, remaining essentially constant at approximately 98 percent over the pressure ratio range of 40 to 1,000. At simulated launch conditions ($P_c/p_o \sim 40$), the area-ratio-25 annular nozzle had a thrust ratio of 0.98, compared with 0.91 and 0.80 for an equivalent $\epsilon = 25$ C-D nozzle with and without separation, respectively, and 0.95 for an $\epsilon = 8$ C-D nozzle. External expansion thus allows nozzles with higher area ratios to be used while maintaining at least the same thrust capability at "take-off" as for vehicles with conventional C-D nozzles. As evidenced by the data, there was no measurable effect of Mach number (i.e., quiescent-air results were essentially the same as those obtained at Mach 2 and 3).

Performance data obtained with an 8:1 C-D nozzle are also included in the figure. This nozzle was run to validate the level of force data and establish confidence in the force measurements. Comparison with the data of reference 4 shows generally good agreement.

To explore the significance of these improvements in nozzle thrust from an overall vehicle performance viewpoint, some cursory consideration was given to an actual large booster application. As shown in figure 5, a representative boost trajectory (altitude versus time) was assumed for a large (million-pound) vehicle. Corresponding thrust coefficients for three nozzle configurations (an $\epsilon = 25$ annular internal-external-expansion nozzle, an $\epsilon = 8$ and an $\epsilon = 25$ C-D nozzle) are presented in this figure along with the thrust coefficients for a theoretical ideal nozzle. The superiority of the annular nozzle over the $\epsilon = 8$ C-D nozzle occurs primarily at the higher altitudes and is indicated by the shaded area. Its superiority over the $\epsilon = 25$ bell C-D nozzle occurs at the lower altitudes and is indicated by the cross-hatched area. The time-integrated thrust coefficient for the $\epsilon = 25$ annular nozzle is 3 percent larger than that for the $\epsilon = 8$ C-D nozzle and 6 percent larger than that for the $\epsilon = 25$ bell C-D nozzle.

With the assumption that there is no significant difference in engine weights with the various nozzles, these results would indicate that, compared with an $\epsilon = 8$ C-D nozzle, the annular nozzle could (with the same initial vehicle gross weight) carry 17 percent more orbital payload. Engine size (or throat area) and the mass fractions of the upper stages were assumed fixed. Because the C-D nozzles will probably require some heavy heat shields in the base area, the assumption of equal engine weights appears reasonable.

Jet Flow Observations and Thrust Vector Control:

Visual observations of the exit flow patterns on the $\epsilon = 15$ annular internal-external-expansion nozzle are shown in the schlieren photographs of figure 6. The patterns are presented for nozzle pressure ratios below, near, and above the design value. At below-design conditions ($P_c/p_o = 43$), the flow did not fill the nozzle exit annulus but followed the external ramp contour with no indication of separation. This observation was supported by the survey rake data. Along the ramp, the static pressures remained at approximately ambient pressure. Near design, the flow filled the nozzle and appeared to be fairly uniform and parallel with the free-stream direction. Above design, the jet diverged or flared out from the nozzle centerline.

Results of deflecting flaps from the external expansion surface into or out of the jet for thrust vector control are shown in figure 7. A 20-degree deflection of a single flap (10.9 percent of the ramp circumference) on the $\epsilon = 25$ annular nozzle produced a side force equal to 4 percent of the axial thrust. Deflecting a similar flap on the opposite side doubled the sideforce, and gave an effective gimbal angle of approximately 4.5 degrees. As shown by the data in the lower portion of the figure, the loss in axial thrust was small (within the scatter of measuring accuracy) with flap deflections up to 20-degrees and flap widths up to 11 percent of the circumference.

Concluding Remarks:

The annular internal-external-expansion rocket nozzle proposed herein for large-thrust booster applications can be regarded as a refined cluster configuration with excellent aerodynamic characteristics in terms of "off-design" performance, base heating effects, and thrust vectoring capabilities. As illustrated, in figure 8, the geometry of an actual installation might be significantly modified from that of the present study. In the experimental model the length of shroud from the bleed inlet to the nozzle lip was inordinately long because of the long thin hollow struts and settling chamber required with the ducting of the high-pressure air. The bleed inlet system need not necessarily be annular, but could consist of several flush slots, as suggested here. The protruding external-expansion surface can be significantly shortened by using a conical rather than a contoured surface. Considerable data is available in the literature to support the supposition that this shortening would not effect the nozzle performance. A more accurate assessment of the overall merit of annular rocket configurations necessitates detailed structural weight analysis and vehicle integration studies. With the annular configurations, parallel concentric boosters or airbreathing boost stages in the center of the annulus offer some other interesting possibilities for future consideration.

ASYMMETRIC "PENSHAPE" NOZZLES IN 'JET CANARD' CONFIGURATIONS

Let us now turn out attention to the steering, or control, aspects of very large vehicles. For boosters with millions of pounds of thrust, conventional methods of gimbaling or throttling of large engines incur severe penalties in terms of structural weight and mechanical complexity.

Jet Canard Concept:

As illustrated in figure 8, one solution to this might be the use of a jet canard on the uppermost stage of the vehicle. The objective of this approach is, first of all, to remove the steering function from the main propulsion system and to take advantage of the long moment arm that results from positioning the control in the uppermost stage. Generally, in the very large vehicles the booster is apt to be quite stubby and the center of gravity for the entire vehicle will be located well down in the booster stage. From the uppermost stage, the required control moments could be provided for all stages of the vehicle.

The jet canard, in concept, would provide a combination of both aerodynamic and reaction control. In the sensible atmosphere aerodynamic forces on the canard surfaces would achieve the necessary side forces. At launch and in the low-"q" and space portions of the mission, a reaction jet discharging from the base of the canard fins might be used.

"Penshape" Nozzle Design:

For these canard control rockets, an asymmetric external-expansion "penshape" nozzle appears attractive. As illustrated in figure 9 and discussed in reference 5, the "penshape" nozzle design is derived by tracing streamlines through a known flow expansion field — in this case, a two-dimensional Prandtl-Meyer flow expansion around a corner. This tracing technique may be applied with the specification of any arbitrary cross-sectional flow area (e.g. a circular exit jet streamtube or a circular sonic throat area). In the case of the canard rocket, a circular throat has been assumed. This then results in a flat elliptical jet streamtube. The nozzle thus has a conventional round throat area adaptable to usual combustor practice. The supersonic expansion surface, however, is a highly asymmetric thin sugar-scoop-type configuration.

Such a geometry lends itself to unusual packaging arrangements on a vehicle — the jet canard being representative of one type of application. Possible details of such an application are suggested in the lower portion of figure 10. Here the combustors are depicted as spherical and the motors as rotatable about a point near the throat. Four canard fins are illustrated in this application. Various degrees of side force could be generated by differential rotation of the motors or flaps on the expansion surfaces, by differentially varying the chamber pressures, or by pulse operation of the motors.

Experimental Apparatus:

To explore the aerodynamic feasibility of the asymmetric external-expansion "penshape" nozzle for jet-canard application, an experimental cold-flow study was conducted in the Lewis 2- by 2-Foot Wind Tunnel. The experimental model is shown at the top of figure 10. The configuration had two simulated canards with the jets discharging from the base area at various angles to the body axis. The "penshape" nozzles had 1/4-inch-diameter circular throats and a design area ratio of 8. To simulate motor rotation, interchangeable nozzle sections were used to vary the discharge angle up to 90 degrees with respect to the free-stream direction. Bottled nitrogen was used to simulate the jet with pressures up to 600 psia. With the nozzles mounted on a strain-gage balance system, performance was obtained in quiescent air and at Mach 3.88.

Nozzle Thrust Performance:

Shown in figure 11 are the "penshape" nozzle thrust characteristics. As previously done, the ratio of thrust to ideal thrust (in the direction of the thrust vector at each pressure ratio) is presented as a function of nozzle pressure ratio. As is typical of external-expansion configurations, the "penshape" nozzle thrust ratio is insensitive to pressure ratio at below-design conditions. For comparison, the performance of an area-ratio-8 C-D nozzle is also included. With this limited data, there was no detectable difference in performance of the nozzle in quiescent air or in a supersonic stream at Mach 3.88.

Nozzle Flow Patterns:

Characteristic flow patterns of the jet canard with "penshape" exhaust nozzles are shown in figure 12 for pressure ratios below and approximately equal to the design value. In both cases, the flow follows the contoured expansion surface with no indication of separation. This is shown by the jet flow at the trailing edge (or point) on the nozzle. As pressure ratio was increased, the flow continued to fill the nozzle until at design conditions the jet was exiting uniformly in the vector direction determined by nozzle orientation.

Concluding Remarks:

The "penshape" nozzle is a high-performance external-expansion design that lends itself to unusual packaging arrangements on a vehicle — e.g., the jet canard. The canard configuration is aimed at combining aerodynamic and reaction control. By its location on the uppermost stage, the steering function is removed from the main propulsion system and advantage is taken of the long moment arm. Undoubtedly, this does not come "free." The assessment of its overall merit will require detailed weight analyses (taking into account the obvious bending moments that the vehicle structure must endure) and further vehicle integration study. The unconventional "penshape" nozzle has been demonstrated to have excellent "off-design" thrust performance. Current work is underway to define jet spreading characteristics insofar as the adjacent structure might be influenced by temperature effects under certain conditions.

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3. Rao, G. V. R.: A New Concept in Rocket Exhaust Nozzles. Presented at ARS Semi-Annual Meeting, May, 1960.

4. Farley, John M. and Campbell, Carl E.: Performance of Several Method-of-Characteristics Exhaust Nozzles. NASA TN 293, 1960.

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APPENDIX

SYMBOLOGY

A_e	projected nozzle-exit area
A_{th}	nozzle throat area
C_T	thrust coefficient, $T_N/P_c A_{th}$
M	Mach number
m	nozzle mass-flow rate
N_F	normal force
P	total pressure
T_N	axial net thrust
T_{Ni}	ideal net thrust, mVi
T_{No}	resultant net thrust
Vi	ideal nozzle-exit velocity
ϵ	nozzle area ratio, A_e/A_{th}

Subscripts:

c	combustion chamber
i	ideal
N	nozzle
O	free stream

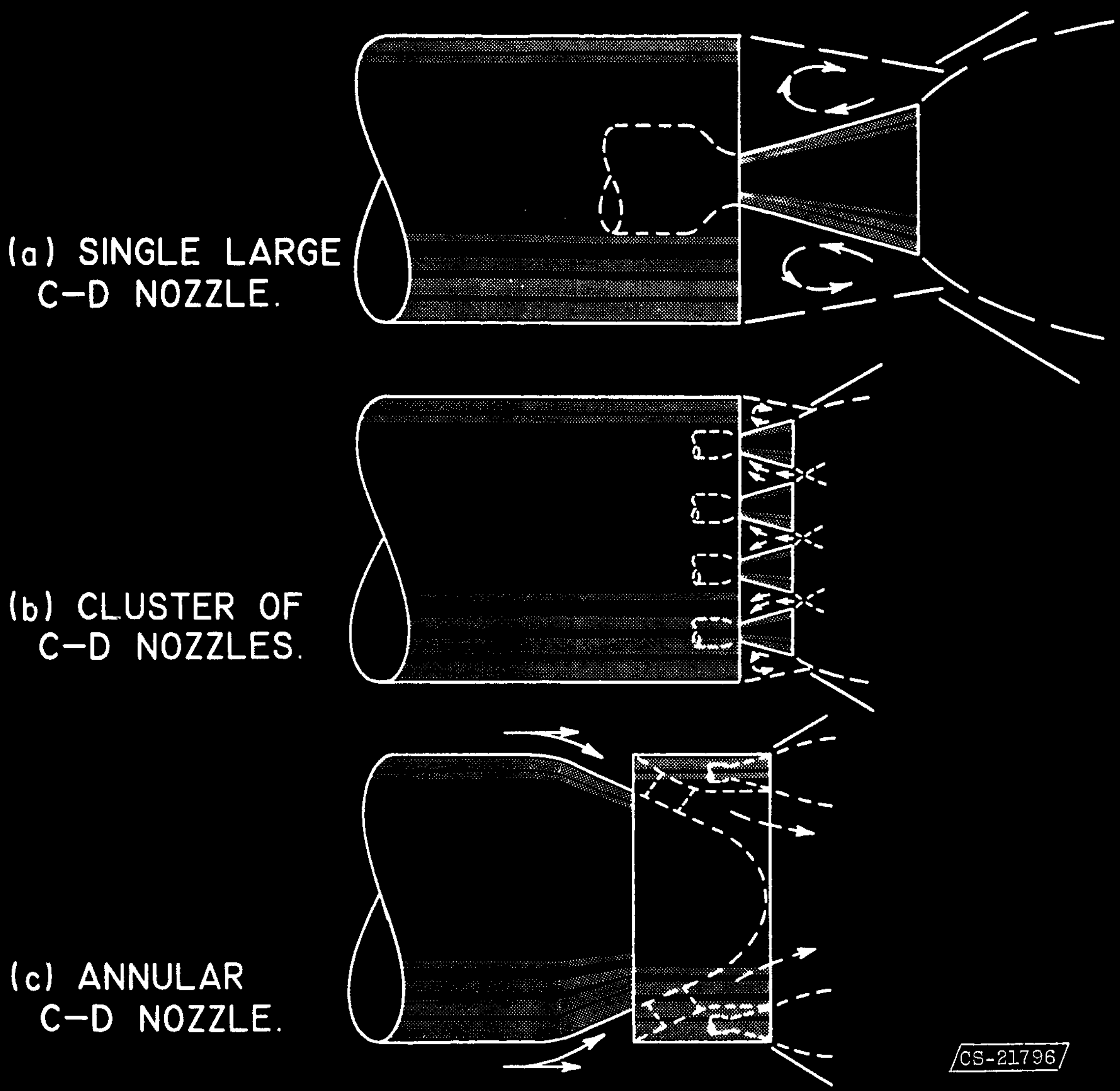

FIGURE 1. - EQUIVALENT NOZZLE SYSTEMS FOR A GIVEN LARGE THRUST APPLICATION.

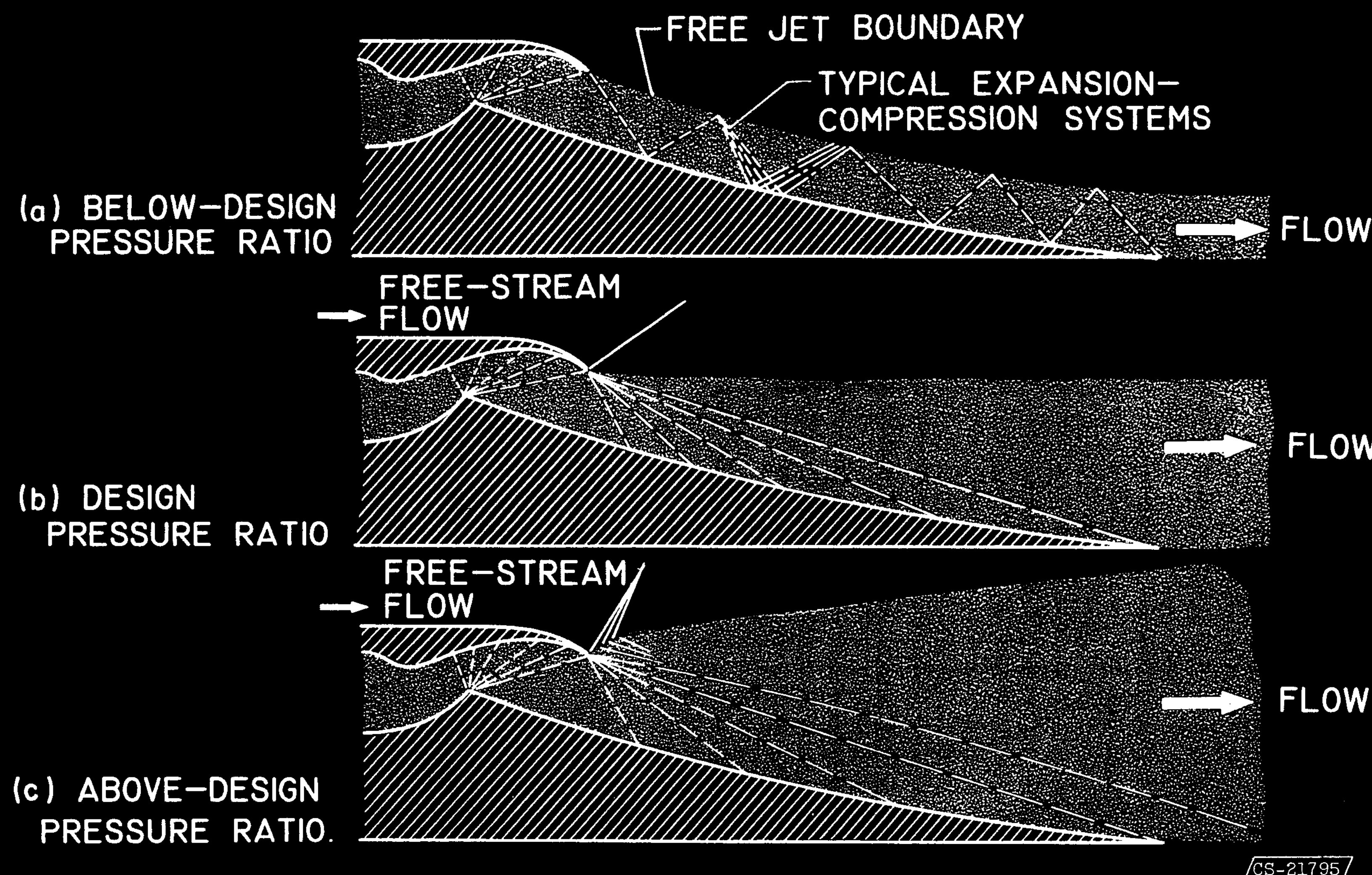

FIGURE 2. - FLOW PATTERNS FROM AN ISENTROPIC INTERNAL-EXTERNAL EXPANSION NOZZLE.

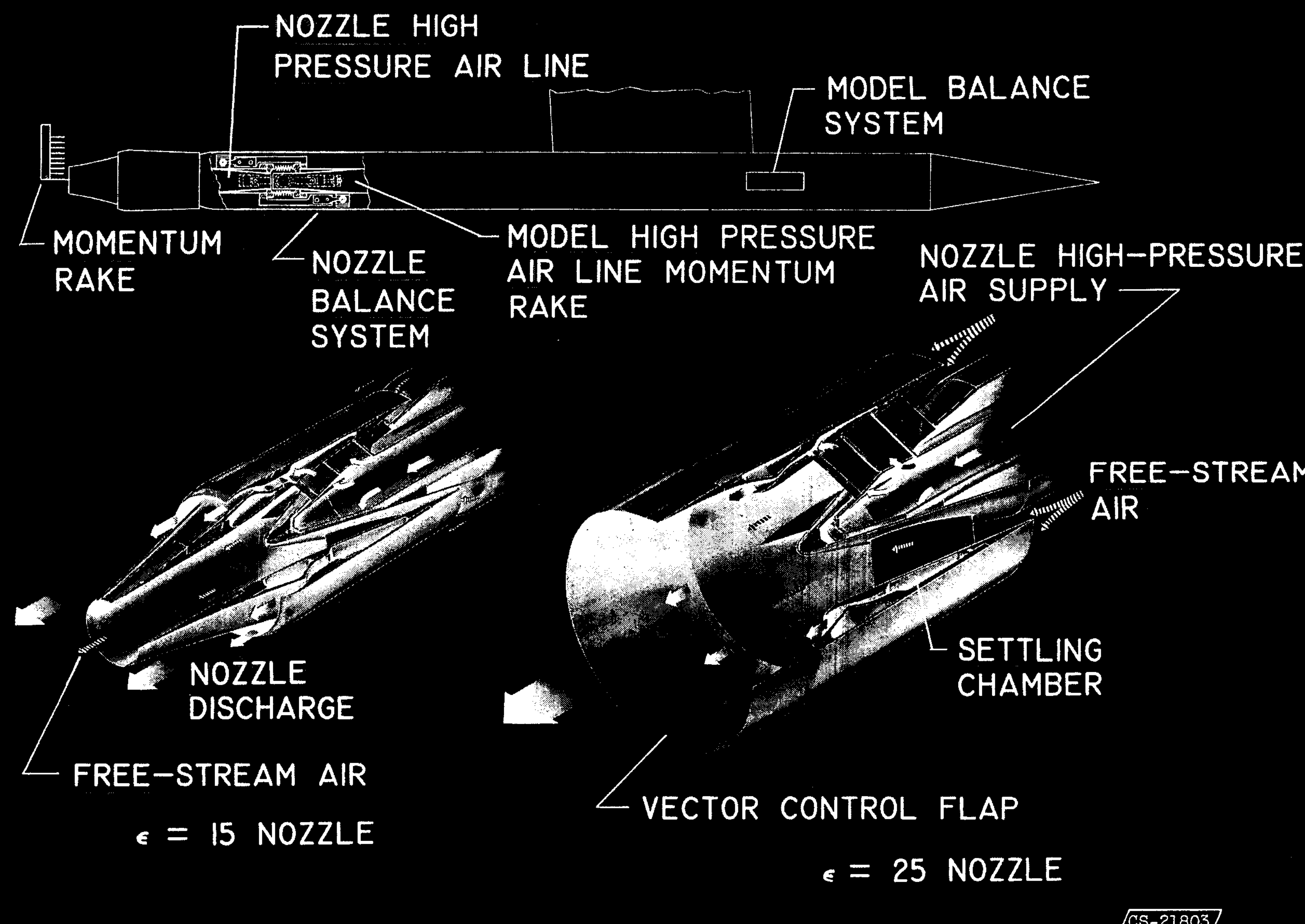

FIGURE 3. - 10 x 10 SWT ANNULAR NOZZLE INVESTIGATION.

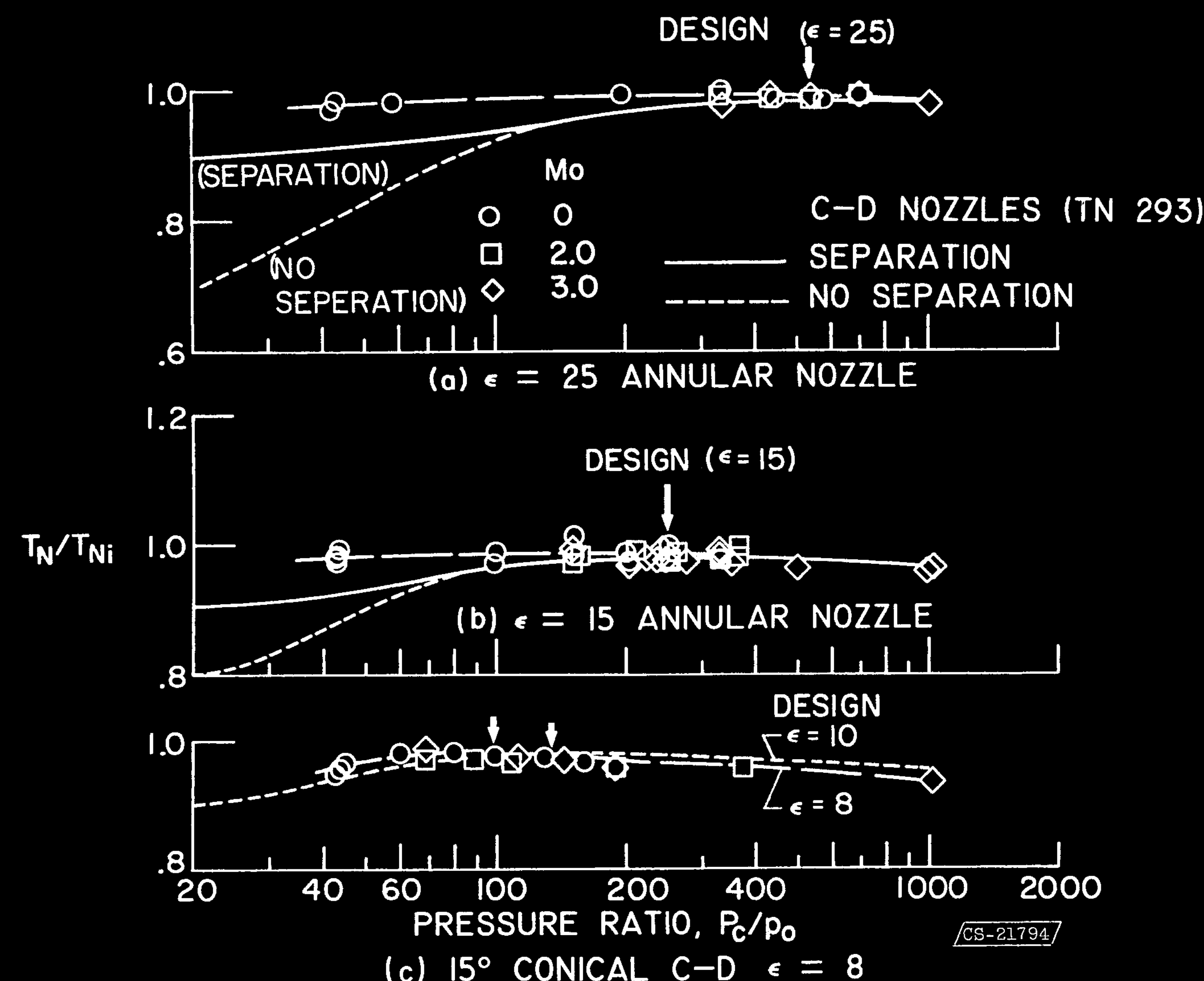

FIGURE 4. - NOZZLE THRUST PERFORMANCE.

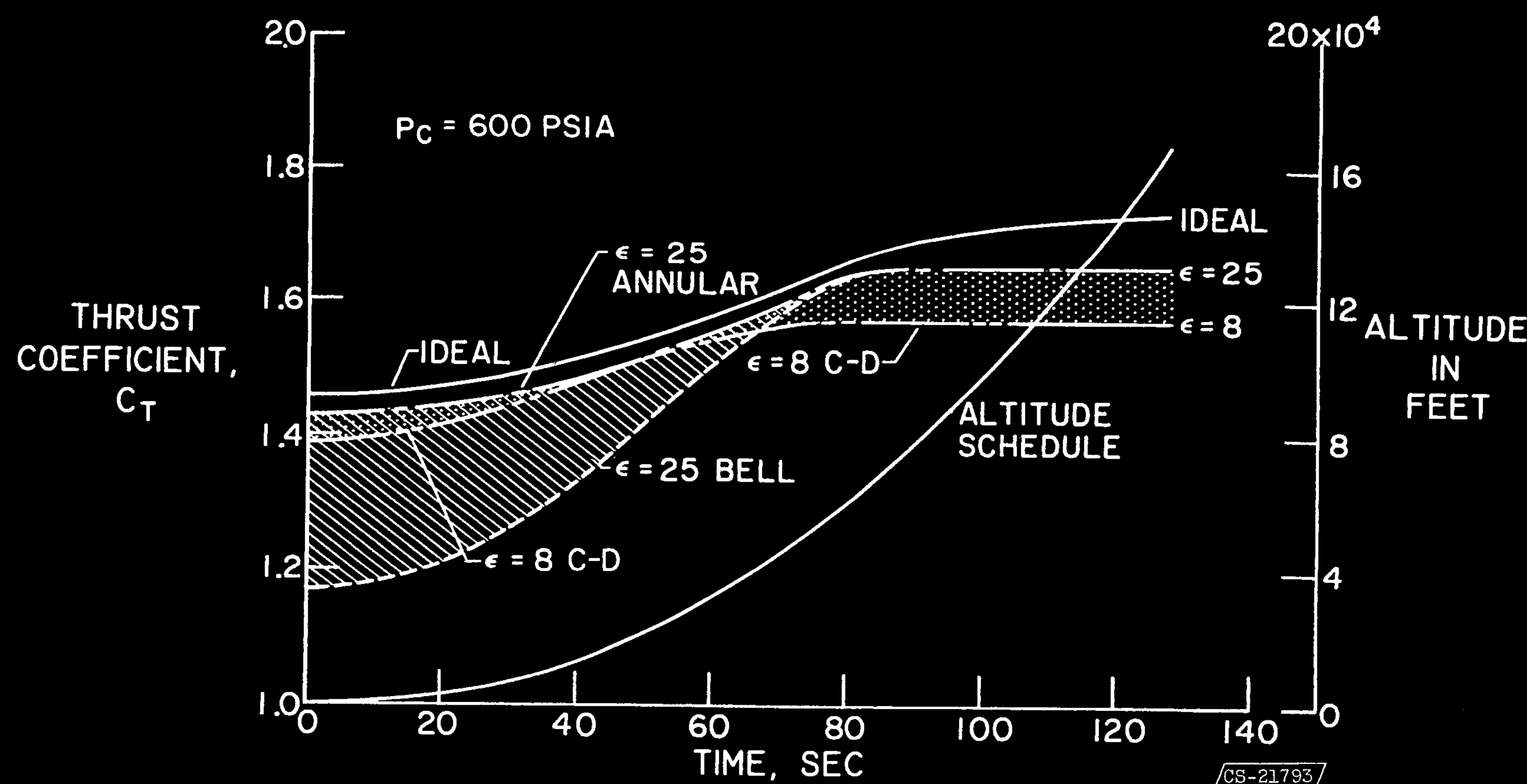

FIGURE 5. - THRUST COMPARISON FOR A TYPICAL SATURN BOOST MISSION.

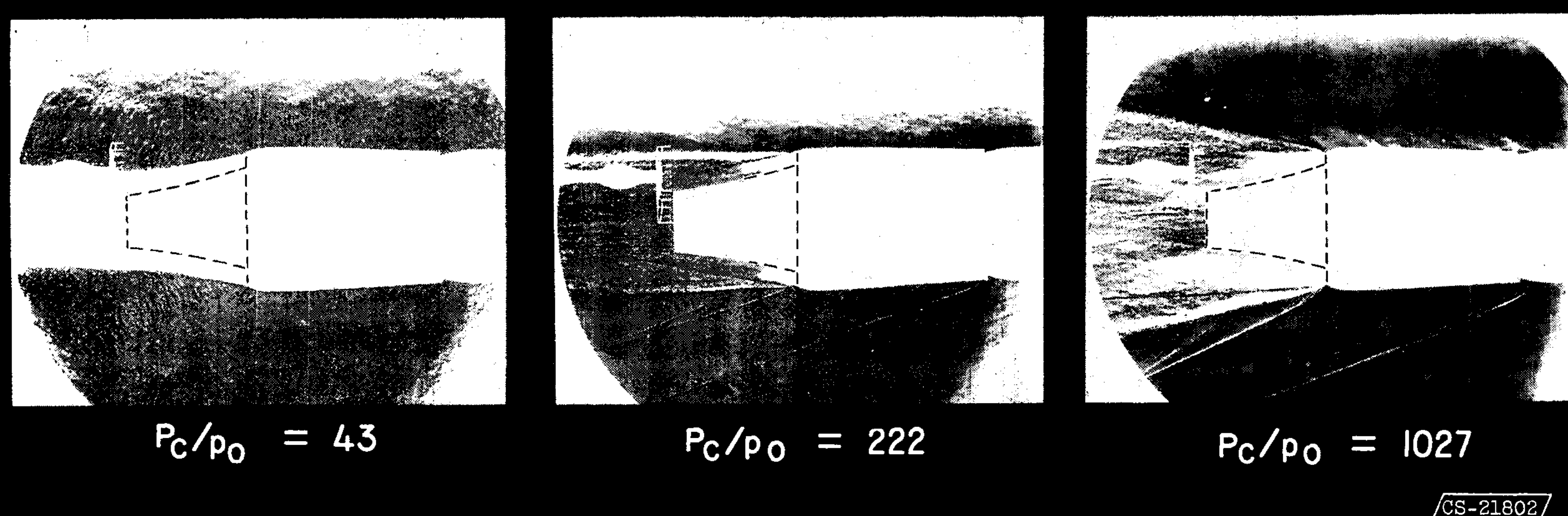

FIGURE 6. - ANNULAR $\epsilon = 15$ NOZZLE EXIT FLOW PATTERNS.

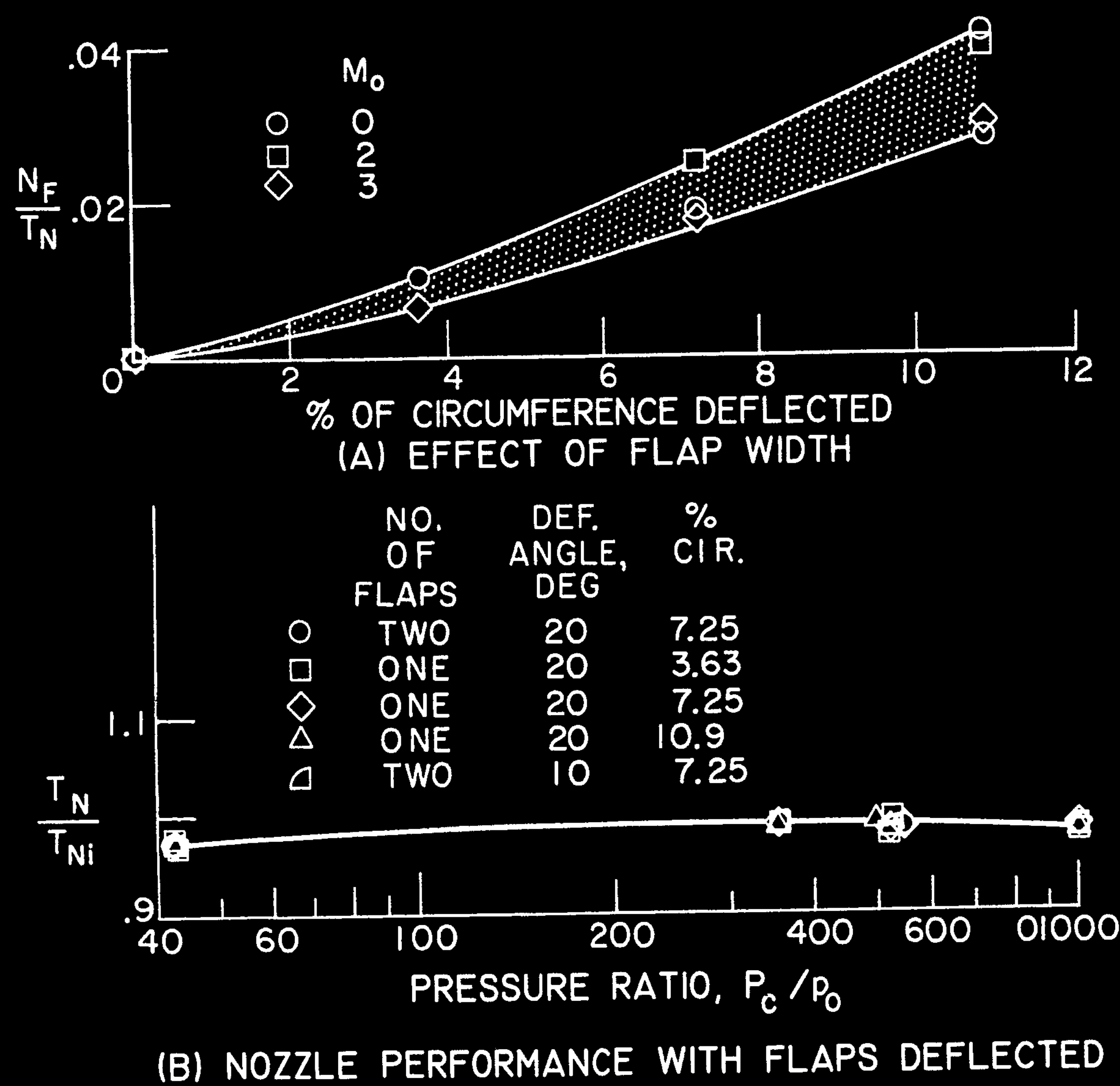

FIGURE 7. - THRUST VECTOR CONTROL (ϵ = 25 ANNULAR NOZZLE).

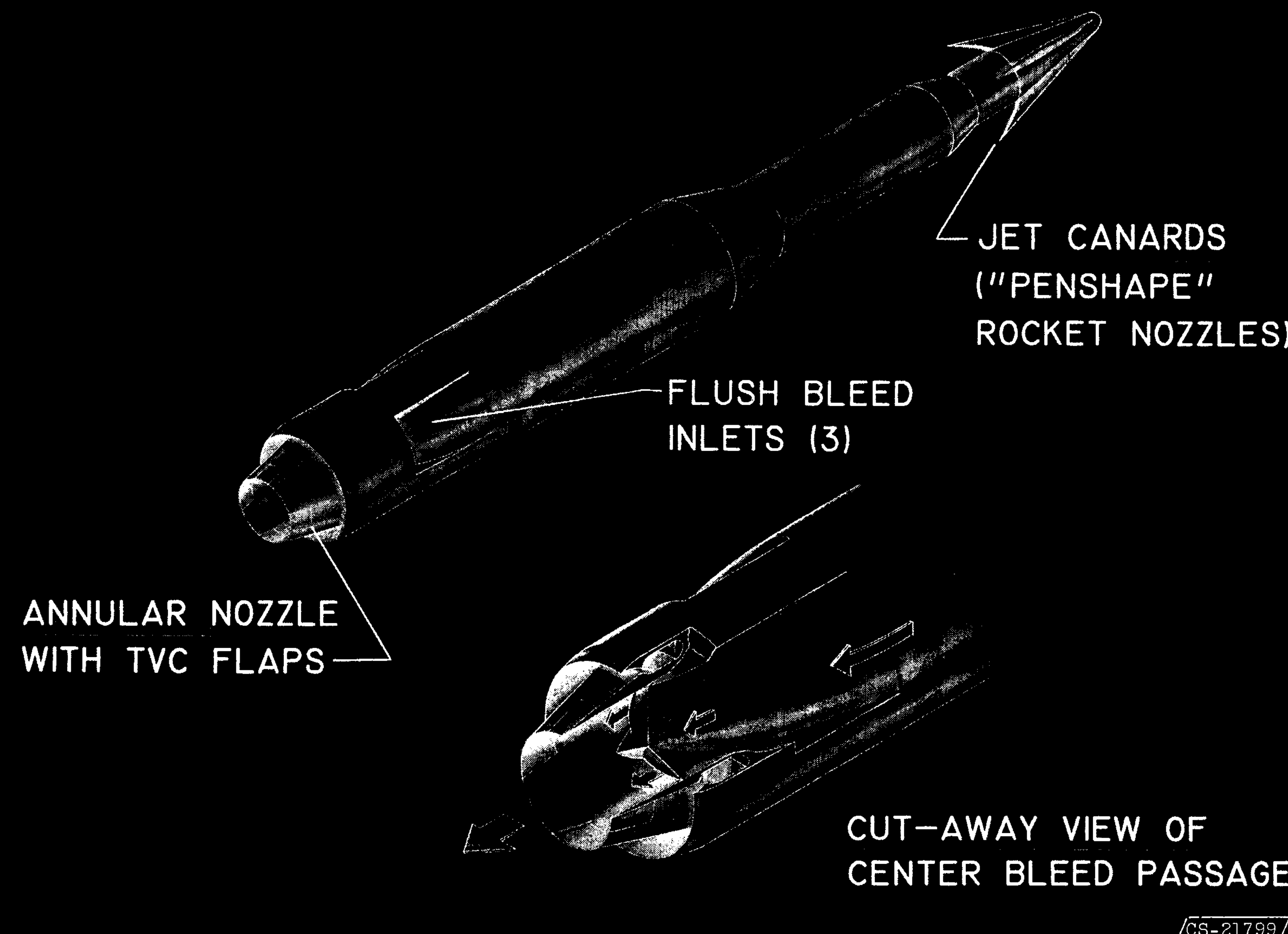

FIGURE 8. - NASA ANNULAR NOZZLE AND JET CANARDS.

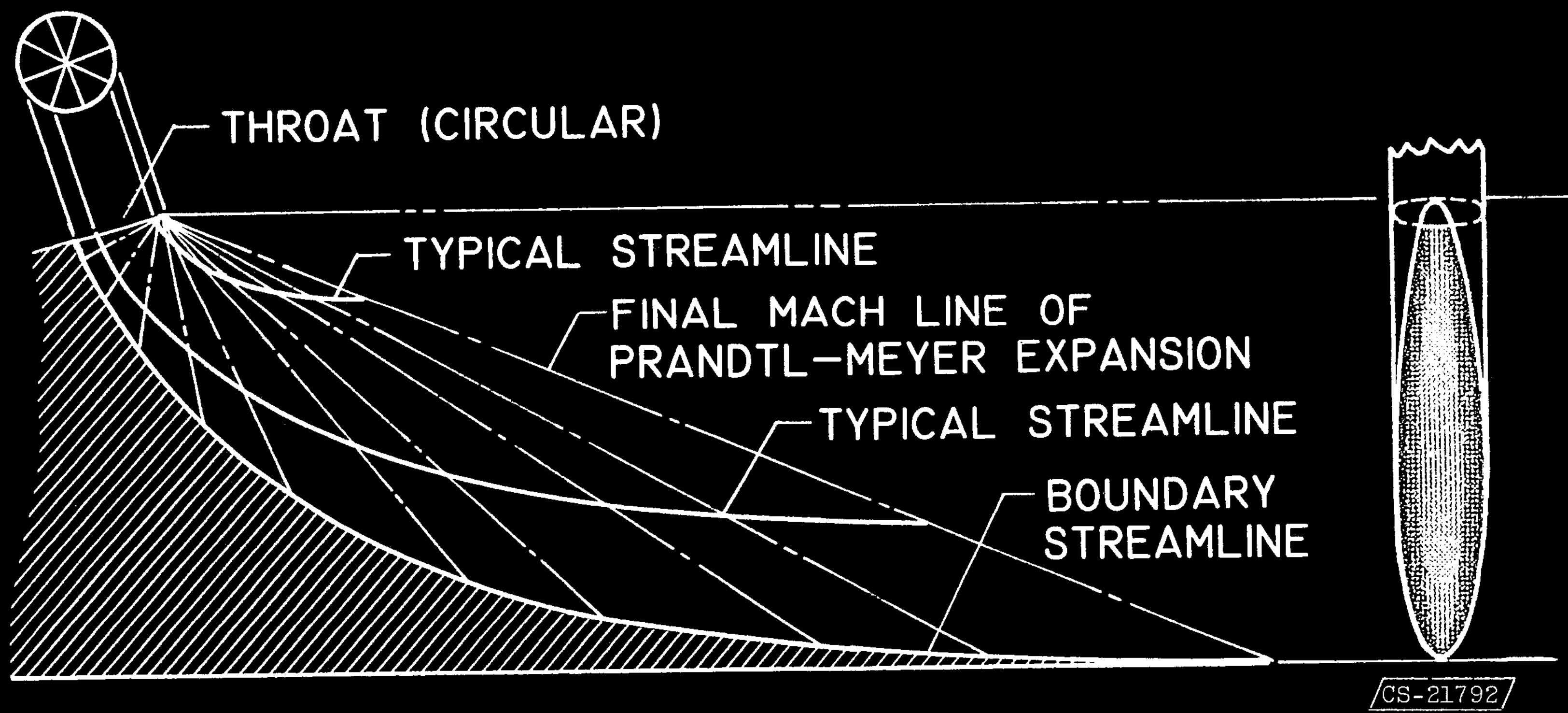

FIGURE 9. - "PENSHAPE" NOZZLE DESIGN PHILOSOPHY.

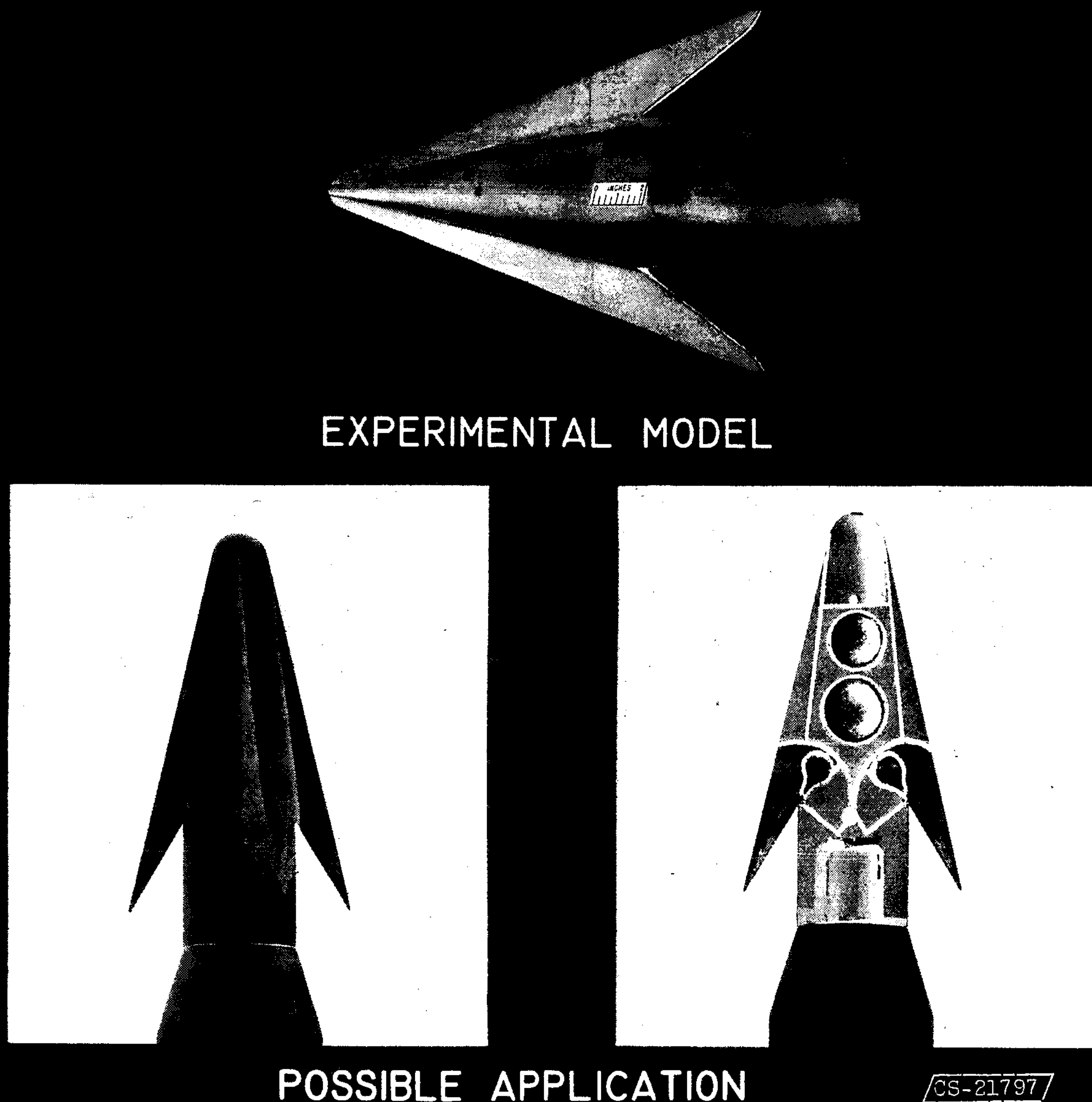

FIGURE 10. - JET CANARDS.

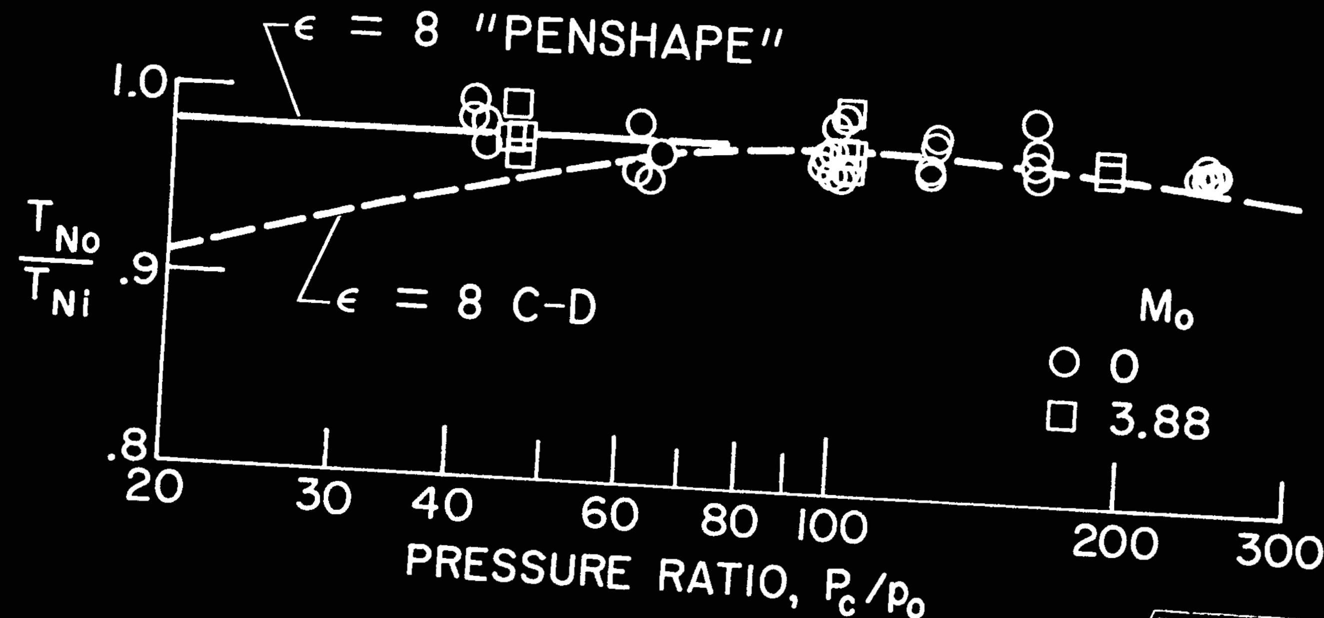

FIGURE 11. - "PENSHAPE" NOZZLE PERFORMANCE.

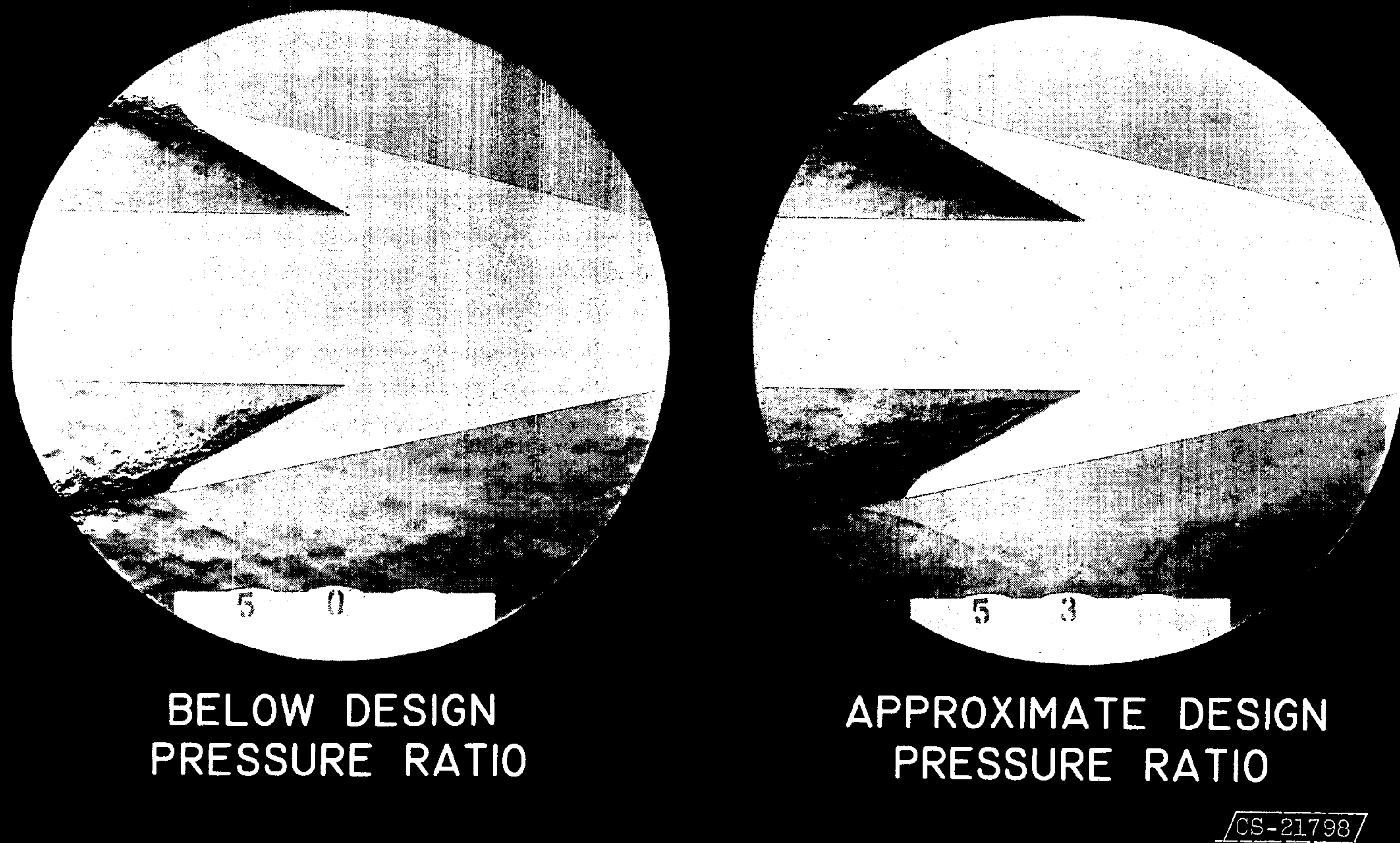

FIGURE 12. - CHARACTERISTIC FLOW PATTERNS OF JET CANARD WITH "PENSHAPE" EXHAUST NOZZLES.